AD-A190 951 MODELLING SEASONALLY FREEZING GROUND CONDITIONS(U) BRISTOL UNIV (ENGLAND) M G ANDERSON ET AL. JUL 87 R/D-5806-EN-01 DAJA45-87-C-0036 1/1

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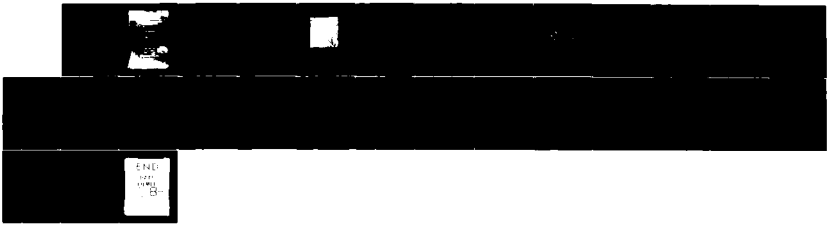

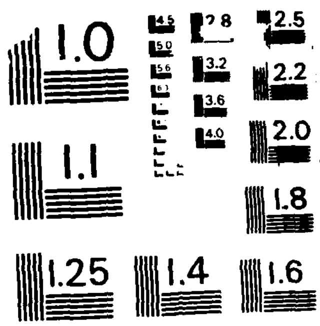

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AD-A190 951

SNOWMELT DISTRIBUTION MODEL (program SNOWM) - PROPOSAL

Snow Distribution Model (program SNOWM) - Proposal

A : Introduction

(1) Aim

Snow and frozen ground are active agents influencing the landscape of the cold regions (high latitude or high mountain areas) today. Frozen ground is dominant in periglacial areas whereas in areas experiencing seasonally frozen ground the action of snow becomes important with, and as well as, frozen ground. Snow is important as a geomorphological and hydrological agent in itself, not only as a component of the hydrological or glacial cycles.

Snow accumulates and then melts or compacts. Differential accumulation and melt, due to external climatic and topographical and internal physical factors, cause spatial (see fig. 1), temporal, e.g. seasonal snow, firn neve ice, and physical, e.g. formation of ice lenses, differences in the snowcover. This project, therefore, aims to model the spatial distribution of snowcover in areas experiencing seasonally frozen ground. The modelling of snow distribution will form the main part of the project (program SNOWM), with the possible coupling of this, at some stage, to a ground temperature model.

(2) Operational objectives

The proposed snow distribution model (SNOWM) is to be developed with the inclusion of the following operational criteria:

a) Satisfactory numerical and areal representation of snow accumulation and melt at any one time, thereby resulting in a knowledge of the snowcover distribution at one time.

b) SNOWM will be a physically-based model and an amalgam of the main types of snowmelt models currently in existence, i.e. the energy-budget and the temperature - index.

c) Aspect is specifically included in SNOWM. In areas not exposed to rapid, frequent air mass and therefore air temperature changes (i.e. unlike Britain) solar insolation is the dominant factor affecting snow distribution, especially during the melt season. Aspect is one of the most important factors affecting solar insolation and therefore snow distribution. For example, in the W1 watershed, Vermont, it has been noticed that:

> "Most of the watershed has predominant southwest, southeast and northeast aspects. This along with the range in elevation, helps create differences in precipitation, depth and duration. This is exemplified by striking differences in snow cover depth during the winter and spring melt period throughout the watershed."
>
> Anderson, E.A. et al. (19")

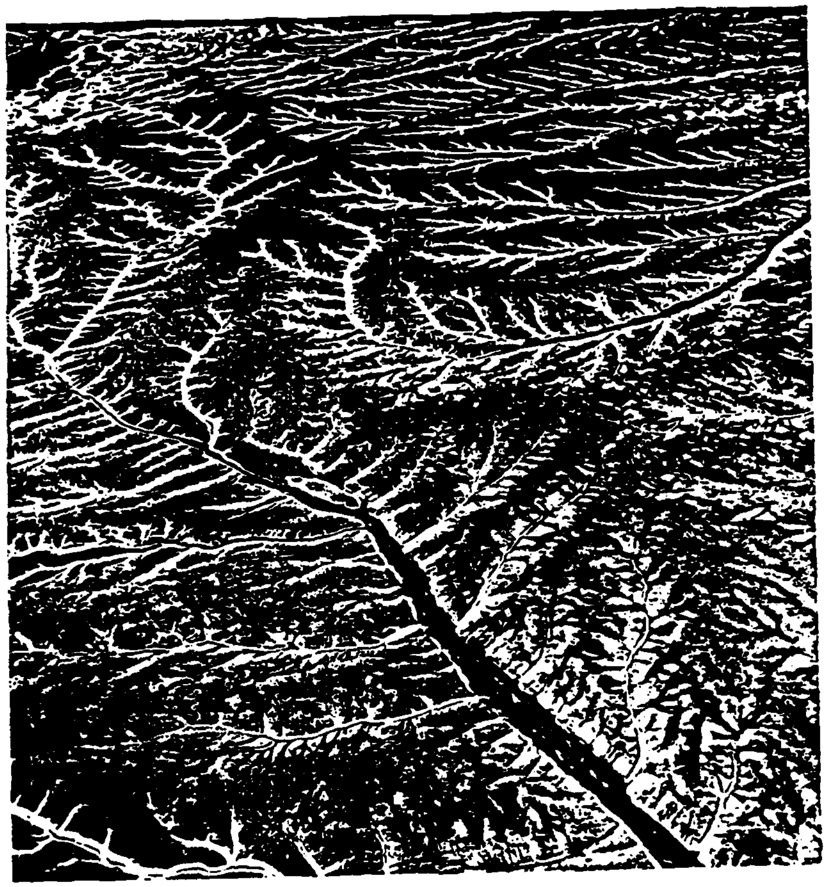


Fig. 1 : The drainage network is highlighted by the distribution of the snowcover, which is concentrated in the channels (Hamelin and Cook, 1967)

d) SNOWM is to be developed for a small catchment area (less than 10 km^2, see section (4)). A basic cellular structure is envisaged for SNOWM (as for example the SHE or VSAS-2) and therefore it should be feasible to decrease or increase the size of these cells depending on the size of the catchment that is being modelled.

e) SNOWM will model the 'snow season', i.e. when snow occurs which is on average between four to eight months in a year (in the northern mid-high latitudes). The model will use daily data but the calculation time-steps can be any required value less than 24 hours, i.e. 5 minutes, 1 hour, etc. The length of these time-steps will vary according to the speed or accuracy required (the shorter the time-step the slower the model).

f) The results will be presented in a spatial form (i.e. some sort of map form) as well as the usual graphic and table forms. The style of O'Loughlin (1986) is envisaged.

g) The presence/absence of vegetation and its effect needs to be included in the modelling.

h) SNOWM is required to be flexible enough to be applied to a variety of catchments with varying degrees of data coverage. Data required is to be kept to a minimum to ensure that this can happen.

i) SNOWM will work in conjunction with a ground temperature model for seasonally frozen ground. However, a future project could run SNOWM in conjunction with a ground temperature model for permafrost.

j) SNOWM should produce results that enable the coupling of SNOWM to pre-existing mass movement or hydrological models. For example, areas or times of potential landslip or flooding can be defined in this way as can the importance of snow distribution to landscape formation and landform development.

The originality of the model and project lies in the inclusion of aspect in the semi-energy budget model as a factor influencing snow distribution and in the scale and flexibility of SNOWM.

(3) Background - existing models

Morris (1985) summarises the existing snow model types. The models forecasting snowmelt over a catchment can be divided into regression, conceptual (temperature-index and energy-budget) and distributed models. The models forecasting snow accumulation are less common but would broadly fall into the first two categories. Distributed models are rare. SNOWM is based on an energy-budget model (see section (4)) but will also have a temperature-index approach in some parts. The basic model stfucture will be cellular and the interaction of water between these cells during melt will

be modelled, if project time allows, using a distributed approach. It is therefore hoped that in this way the model will maximize the advantages of the different model types and minimize their disadvantages.

Temperature-index models usually use data that is simple to collect or readily available from existing sources and the quantity of data required is small. Their disadvantages are that they tend towards being catchment specific, because of parameterization, and the modelling of the physical interactions (processes) tends to be less well defined. Conversely, energy-budget models define the physical interactions well but, because of this, require a lot of detailed, hard-to-obtain data and make the model itself bulky, harder to manipulate and expensive.

It must be noted that the majority of catchment snow models are concerned with snowmelt and that models involving snow accumulation and snowmelt, modelled over the snow season (autumn to spring) are rare. Areal snow distribution models, of the type envisaged for SNOWM, are also rare.

(4) Proposed model structure and data requirements

SNOWM is based on an existing energy-budget model which calculates the temperature of a surface at the surface/air interface, TSTM (Balick et al. 1981). TSTM calculates surface temperature using energy equations which allow for the modification of the solar energy input by aspect, cloudiness, wind speed, etc. TSTM will be used to calculate either the snow or ground surface temperatures (depending if there is snow present or absent) and is the basis upon which SNOWM is built.

The present data requirements are listed in Table 1. Extensive sensitivity testing will be carried out on SNOWM when it is operational to see if various data can be omitted from Table 1.

SNOWM is being developed for testing on the W3 experiment watershed, Vermont (USA). This is the only catchment with a suitable data coverage. Fig. 2 is a map of W3.

A more detailed description of SNOWM is given in sections B and C.

Present data requirements (Table 1)

Cloud type
Cloud cover (%)
Instrument shelter height
Air temperature (^{o}C)
Relative humidity
Wind speed
Slope angle
Slope aspect
Latitude
Ground temperature
Surface thermal emissivity (i.e. snow/soil)
    "   albedo
    "   saturation
    "   thermal diffusivity
    "   heat conductivity
Vegetation cover (fraction)
    "   state (living or dead)
    "   thermal emissivity
    "   absorptivity
    "   height
Altitude
Precipitation
Catchment area

Aerial photographs or maps of snowcover are needed as an indication of snow presence/absence over the year (or snow season) at W3 in order to verify SNOWM results.

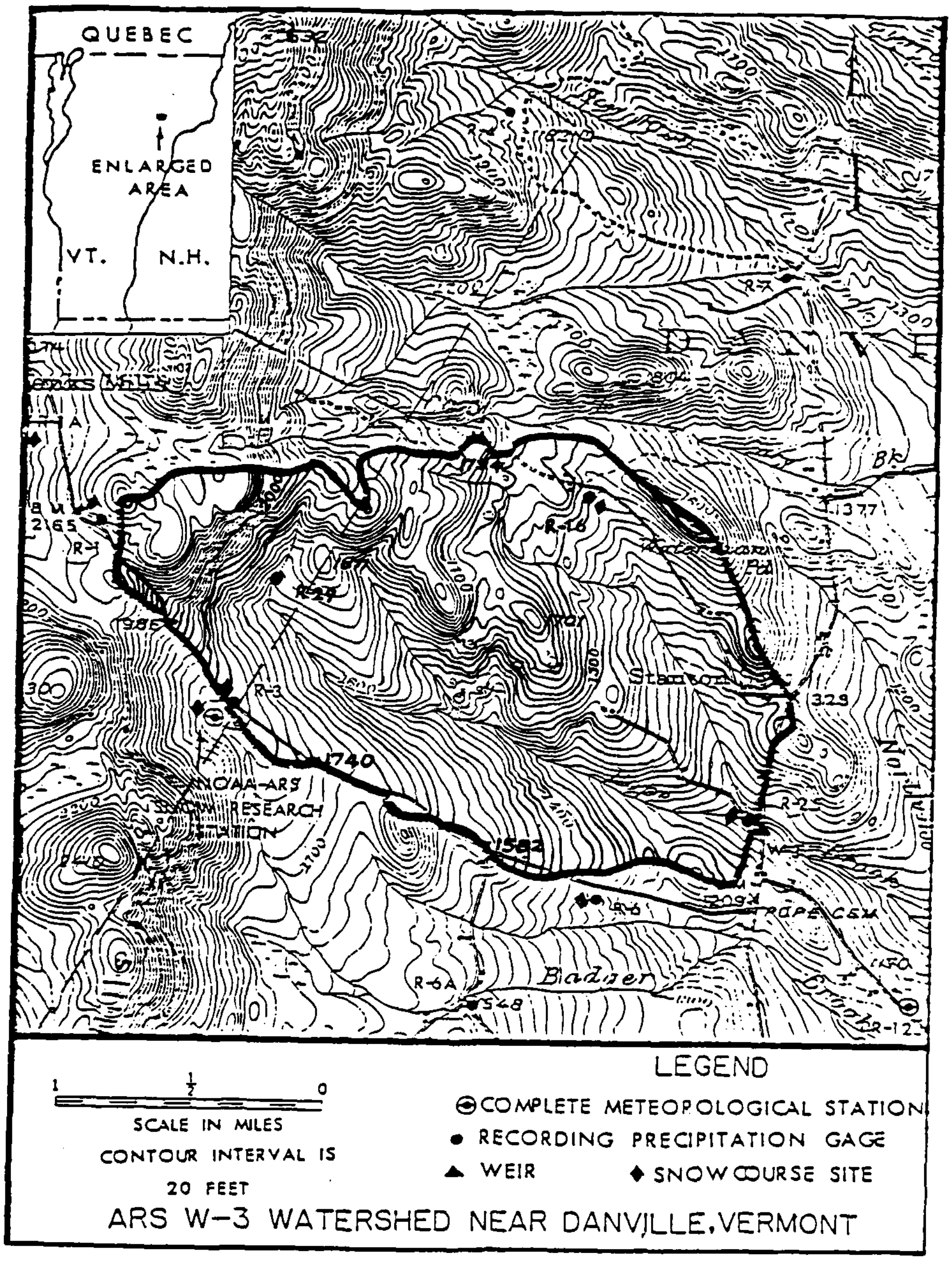


Fig. 2. Topographic map of the W-3 watershed (Vermont), Anderson, E.A. et L. (1977)

B: Proposed Algorithm for SNOWM

(1) Model snow conditions and scenarios (Table 2).

(2) Flow diagram for proposed SNOWM (Fig. 3)

(3) Major equations in SNOWM (Table 3)

(1) At present SNOWM assumes the following conditions:

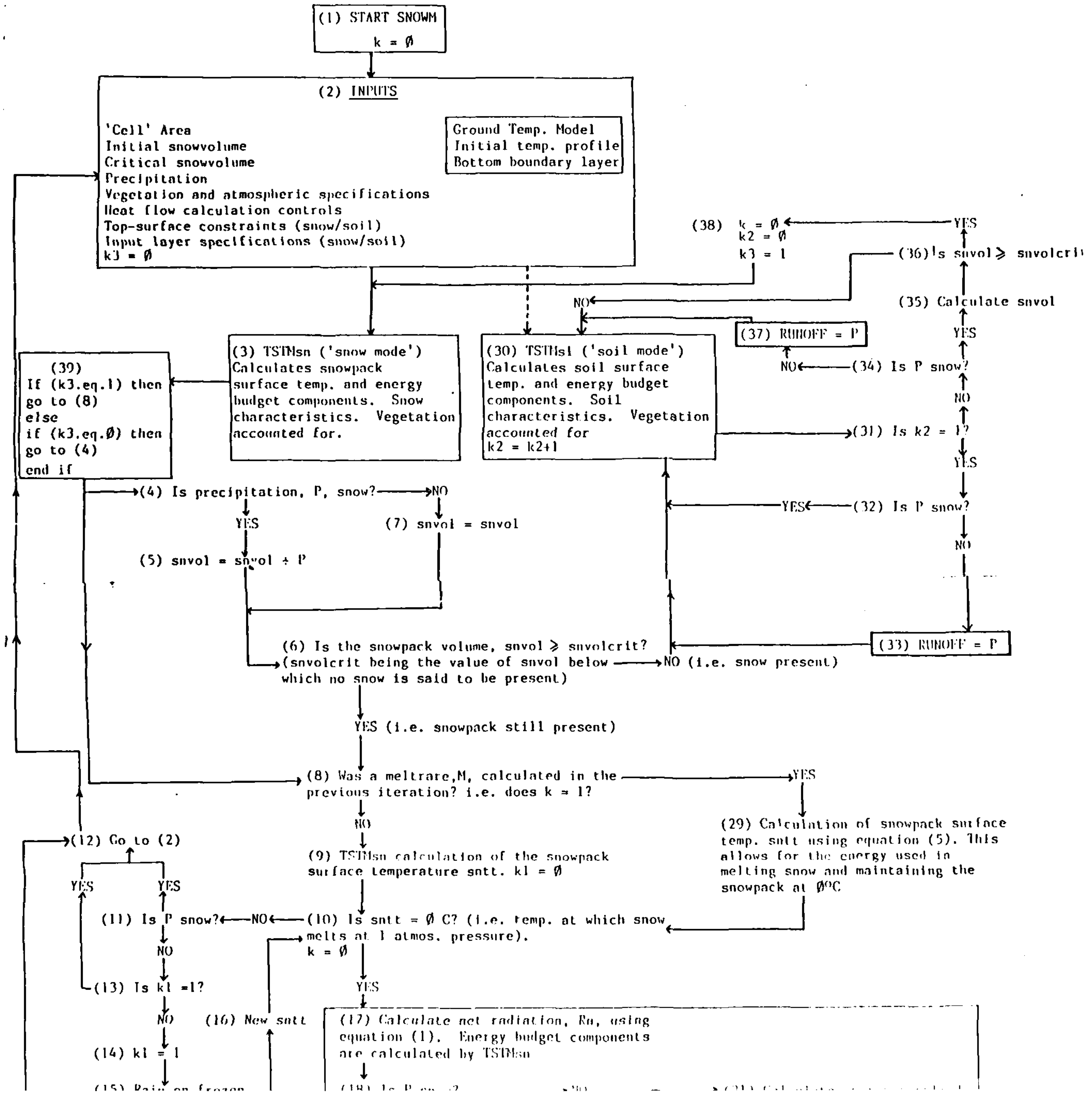
$$\begin{tikzcd} \text{Snow} \arrow[r] & \text{Melting snow (interrupted melting accounted for)} \arrow[r] & \text{No snow} \arrow[ll, bend right] \end{tikzcd}$$

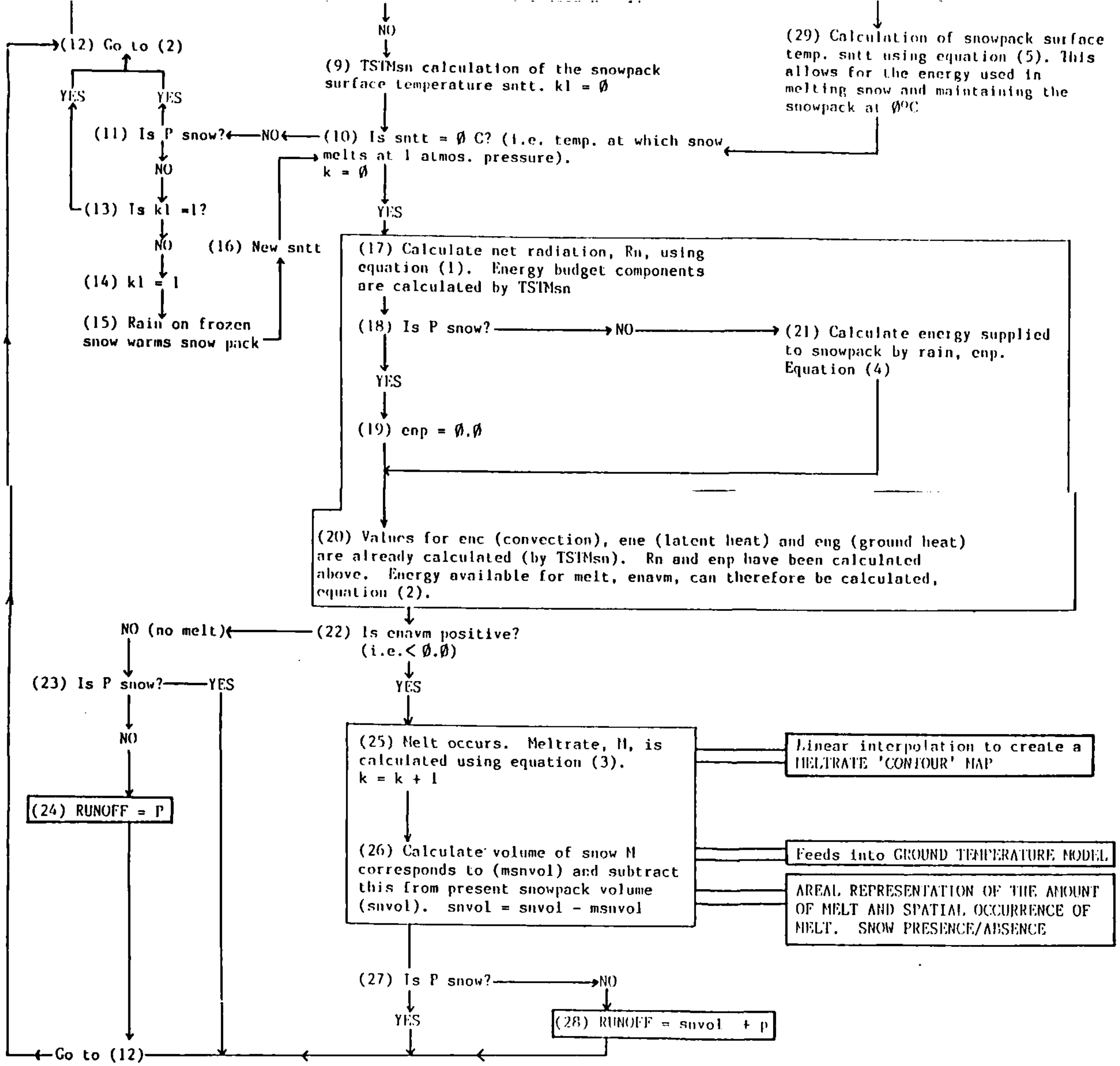
Each numbered step in the flow-diagram is referred to in the sequence that would be followed if the conditions were as shown above. From these conditions 5 snow scenarios are envisaged:

A	Snow present	-	pack $<0^{\circ}C$, no melt
B	Snow present	-	pack at $0^{\circ}C$, energy deficit, no melting
C	Snow present	-	pack at $0^{\circ}C$, energy sufficient for melt to occur for first time
D	Snow present	-	pack at $0^{\circ}C$, melting and melt in previous iteration
E	No snow present	-	melt finished, possible build-up of pack again by additional snowfall

SNOWM allows for precipitation falling as snow or rain on various ground conditions.

(2) Flow diagram for proposed SNOWM (Fig. 3)




NO
(9) TSTMsn calculation of the snowpack surface temperature sntt. kl = Ø
(29) Calculation of snowpack surface temp. sntt using equation (5). This allows for the energy used in melting snow and maintaining the snowpack at Ø°C
(12) Go to (2)
YES
YES
(11) Is P snow?
NO
(10) Is sntt = Ø C? (i.e. temp. at which snow melts at 1 atmos. pressure).
k = Ø
NO
(13) Is kl =1?
YES
NO
(16) New sntt
(14) kl = 1
(15) Rain on frozen snow warms snow pack
(17) Calculate net radiation, Rn, using equation (1). Energy budget components are calculated by TSTMsn
(18) Is P snow?
NO
(21) Calculate energy supplied to snowpack by rain, enp. Equation (4)
YES
(19) enp = Ø.Ø
(20) Values for enc (convection), ene (latent heat) and eng (ground heat) are already calculated (by TSTMsn). Rn and enp have been calculated above. Energy available for melt, enavm, can therefore be calculated, equation (2).
NO (no melt)
(22) Is enavm positive? (i.e.< Ø.Ø)
(23) Is P snow?
YES
YES
NO
(25) Melt occurs. Meltrate, M, is calculated using equation (3). k = k + 1
Linear interpolation to create a MELTRATE 'CONTOUR' MAP
(24) RUNOFF = P
(26) Calculate volume of snow M corresponds to (msnvol) and subtract this from present snowpack volume (snvol). snvol = snvol - msnvol
Feeds into GROUND TEMPERATURE MODEL
AREAL REPRESENTATION OF THE AMOUNT OF MELT AND SPATIAL OCCURRENCE OF MELT. SNOW PRESENCE/ABSENCE
(27) Is P snow?
NO
YES
(28) RUNOFF = snvol + p
Go to (12)

SNOW SCENARIOS: (Table 2)

- with reference to Fig. 3

A Snow present - no melting

(1), 2, 3, 39, 4, 5/7, 6, 8, 9, 10, 11, 12/(13, 14, 15, 16, 10), 2.

B Snow present - pack at $0^{o}C$, energy deficit, no melting

(1), 2, 3, 39, 4, 5/7, 6, 8, 9, 10, 17, 18, 19/21, 20, 22, 23, 24, 12, 2.

C Snow present - pack at $0^{o}C$, energy sufficient for melt to occur for the first time

(1), 2, 3, 39, 4, 5/7, 6, 8, 9, 10, 17, 18, 19/21, 20, 22, 25, 26, 27, 28, 12, 2.

D Snow present - pack at $0^{o}C$, melting and melt in previous time step

(1), 2, 3, 39, 4, 5/7, 6, 8, 29, 10, 17, 18, 19/21, 20, 22, 23, 24, 12, 2.

Can have melt followed by no melt, pack at $0^{o}C$ by energy deficit and pack at $0^{o}C$ and sufficient energy for melt.

E No snow present - melt finished, building of pack by additional snowfall possible.

(1), 2, 3, 39, 4, 5/7, 6, 30, 31, 32, 33, 30,
30, 31, 34, 35, 36, 38, 3, 39, 8, 9 etc. (snow build-up)

(3) Major Equations in SNOWM (Table 3)

Equation 1

Net all-wave radiation, R_n,

$$R_n = S\downarrow - S\uparrow + L\downarrow - L\uparrow$$

$S\downarrow$ solar insolation

$S\downarrow - S\uparrow$ surface absorption

$L\downarrow$ atmospheric IR emission

$L\uparrow$ greybody radiation

Units : $Js^{-1}m^{-2}$

Equation 2

Energy available for melt, Qm (or $\mathcal{L}\rho_w$ M or enavm),

$$\mathcal{L}\rho_w M = R_n + c + e + g + p - \frac{dU}{dt} \quad (Jm^{-2}s^{-1})$$

R_n net radiation

$\mathcal{L}$ latent heat of fusion (Jkg^{-1})

ρ_w density of water (kgm^{-3})

c convection (sensible) heat exchange (enc)

e latent (evaporation, sublimation, condensation) heat exchange (ene)

g heat exchange at ground surface (eng)

p heat content of precipitation (enp)

$\frac{dU}{dt}$ rate of change of internal energy of the snowpack

In the model outline: enavm = R_n + enc + ene + eng + enp

Equation 3

From equation (2) : Meltrate, M;

$$M = \frac{enavm}{\mathcal{L}\rho_w B} \qquad (m.water\ s^{-1})$$

B thermal quality or fraction of ice in a unit mass of wet snow (related to $\frac{dU}{dt}$)

$\mathcal{L}$ latent heat of fusion (Jkg^{-1})

ρ_w density of water (kgm^{-3})

M snowmelt water equivalent (m.water s^{-1})

Equation 4

Rain on melting snowpack, rain does not freeze:

$$Qp = {}_wCp\ (Tr - Ts)\ Pr/1000$$

Qp energy supplied to pack by rain ($kJm^{-2}.day^{-1}$)

ρ_w density of water (kgm^{-3})

Cp specific heat capacity of water ($kJ/(kg^{-1}{}^{o}C^{-1}$)

Tr temperature of rain ^{o}C

Ts snow temperature ^{o}C

Pr rate of precipitation (mm/day^{-1})

Equation 5

Calculation of surface temperature taking into account the energy needed to melt snow at $0^{\circ}C$ (i.e. maintaining the snowpack at $0^{\circ}C$ until melt complete).

$$\text{enavm} = \frac{T^t - T^{t-1}}{\Delta t} . Cp\rho_s \qquad (Jm^{-2}s^{-1})$$

$$\Delta t.\text{enavm} = T^t - Tt^{-1} . Cp\rho_s$$

$$\frac{\Delta t.\text{enavm}}{Cp\rho_s} = T^t - T^{t-1}$$

$T^{t-1} = 0$ because smowpack melting. Isothermal.

$\therefore$ new temp., sntt,

$$\text{sntt} = \frac{\Delta t.\text{enavm}}{cp\rho_s\ d^{t-1}} \qquad (K)$$

d	depth of snow (m)
t	change in time, i.e. one time-step (s)
cp	specific heat capacity of snow ($Jkg^{-1}K^{-1}$)
ρs	density of snow ($kgm.snow^{-3}$)
T^t	temperature at time t (K)

Energy input has to be divided by snowdepth (d^{t-1}) in order to achieve the correct temperature rise in the snow and the correct units for sntt.

C: Detailed description of SNOWM functions

This follows through the flow diagram (fig. 3) step-by-step:

(1) k is a count of melting occurrence. k = 1 if melt has occurred during the previous time step. In scenario A, k = 0 because this is the first state of the model, i.e. no melt has occurred previously

A Snow present - pack $0^{\circ}C$, no melt

(2) Inputs for SNOWM. At present these are quite numerous. It is hoped that by extensive sensitivity testing some less important variables can be excluded (taken as zero or one). This is viable within the semi energy-budget model envisaged. The model TSTM requires a lot of data. Data such as relative humidity and cloudiness are not readily available in many catchments. This problem will be examined further. Some of the data is obtained from a ground temperature model. This is at present in a very early pilot stage and will be examined further.

TSTM operates on a basic 24 hour iteration time. However, the actual time step within that 24 hours, and the print-out frequency of data can be specified as required. For example, TSTM will calculate surface temperature, greybody radiance etc., every 5 minutes within the 24 hours, and then print out hourly averages of those 5 minute time steps (print frequency).

SNOWM is calculating net radiation, solar insolation, etc., and melt rate at a point on a 3D surface. The point is taken as being situated in the centre of a 'cell'. A cell is a polygonal area which is said to have the same characteristics as the centre-point. It is as yet undecided as to how to subdivide the catchment into polygons. Irregular polygons rather than grid squares on a gridiron are to be preferred as grid squares tend to ignore the boundaries of underlying relief, aspect, etc.

(3) TSTM is a US Corps of Engineers model (Balick et al. 1981). TSTMsn and TSTMsl are basically the same model, one with snow characteristics, e.g. albedo, thermal diffusivity, etc. (3), the other with the corresponding soil characteristics (31). The model is explained in more detail in Balick et al. (1981). It is an energy-budget model calculating surface temperature as well as several energy budget components. Some of the inputs, e.g. albedo and thermal diffusivity for TSTMsn will vary according to the state of the snow, i.e. its age, depth, density, contamination (dirty or clean), if there has been rain-on-snow and if this has then frozen, infiltrated, ponded on the surface or run off, if there is melting snow present in the snowpack and if the resultant snowmelt has then frozen, infiltrated, ponded on the surface or run off.

(4) Is the precipitation, P, snow or rain? This question is asked elsewhere in SNOWM as well. The action of rain-on-snow (the snow being in a state of melt or frozen) is important, as is the

accumulation of snow, and the time since last snowfall (density changes with snow and age, etc.). At this stage, any snowfall is multiplied by the cell area and is added to the snow volume total, step (5). The snowfall will have to be converted into water equivalent (this is perhaps more easily done if the resultant new total snowdepth is converted rather than the smaller value for the actual amount of snow that fell during the time step). Small values for snowfall will be obtained if, for example, snowfall/5 minute time step was modelled (the snowfall/day would be extrapolated into 5 min. values). These values are liable to be very small and therefore it might be better to run SNOWM without including the precipitation for each time step and then run SNOWM again, on the averaged, say hourly values. This, however, remains to be seen when the model is operational. At this stage if the precipitation is rain it is effectively ignored and no change in snvol is registered (7).

(6) If snvol is greater than or equal to $snvol_{crit}$ there is snow present. $Snvol_{crit}$ is an arbitrary critical value above which (and equal to) snow is said to be present and below which it is absent. The actual value for this critical snow volume has yet to be decided but it will probably correspond to a snowdepth of about 5 cm. This may be further investigated in the field (i.e. what is the minimum depth of snow which can easily be recorded ?). The use of snow volume instead of snowdepth is discussed in (26). It might be decided to substitute snowdepth or snow water equivalent for snow volume.

(8) The method used to calculate the surface temperature of the snowpack is effected by the presence/absence of melt in the previous iteration. If there was no melt in the previous iteration then the TSTMsn calculation of snow surface temperature, sntt, is acceptable. If there was melt, then SNOWM branches to (29).

(9) Snowpack surface temperature, sntt, is calculated using the model TSTMsn. kl is set at zero. kl is a count ensuring that the SNOWM branch 13, 15 and 16 can only be called once every iteration, and avoiding a perpetual do-loop.

(10) Is the snowpack surface temperature, sntt, $0^{\circ}C$? This is the temperature at which snow melts. The snowpack, if not at $0^{\circ}C$, will be lower than $0^{\circ}C$ (branch (11) onwards). The snowpack should not be greater than $0^{\circ}C$. This should be physically impossibe because snow melts at $0^{\circ}C$ and maintains $0^{\circ}C$ until all melt has finished (i.e. until all the solid water (snow/ice) has changed phase to liquid water). k is set to zero for the second time. This is because, in all but the first time , (1) is bypassed and the program routed to (2). The count k is still required (whether melt occurred in the previous iteration or not is still important) and is therefore reset here (10).

(11) The snowpack is below $0^{\circ}C$ and there is therefore no melting. If the precipitation is rain this will warm the snowpack and create an increased snowpack surface temperature for the time step. This is allowed for by branch 13, 14, 15 and 16. If the precipitation is snow then SNOWM is routed back to (2) for the next time step (the amount of

snowfall has already been accounted for (7)). Kuusisto (1986, p.38) suggests that snowmelt within a snowpack may occur due to solar radiation (because this can be distributed throughout the vertical extent of the snowpack) even if the temperature of the snow surface is below zero. He does not elaborate on this, which will need to be investigated further and, if necessary, be incorporated into SNOWM. No allowance is made for this in SNOWM at present.

(12) SNOWM is routed back to TSTMsn for the next time step calculations.

(13), (14), (15, (16) This loop deals with the effect of rain falling on a snowpack below 0°C, one where no melt is occurring. (13) and (14) are a count ensuring that the loop can only occur once every time step and that SNOWM does not become caught in this loop. (15) calculates the effect of rain on a subzero snowpack. Male and Granger (1978, p.122) give a good account of this effect and use will be made of their equations 35, 36 and 37. The action of rain on a subzero snowpack is significant, for example, rain falling at the rate of 1mm/hr will increase the temperature of a snowpack having a mean temperature of -3°C, a mean density of 240 kg/m^3, and a depth of 30 cm at the rate of 0.6°C/hr. This will be investigated further. The result of the action of rain on the subzero snowpack is an increase in snowpack temperature and therefore in snowpack surface temperature, (16). This is then routed back to (10). This rain-on-sub-zero-snow loop can only occur once in every time step.

B Snow present - pack at 0°C, energy deficit, no melting

(1) to (9) as before (A).

(10) Snowpack surface temperature is 0°C, i.e. the temperature at which snow melts. A problem may occur because of the way in which the air temperatures for each time step are calculated from the measured input temperatures. For example, if because of this the calculated snow surface temperature is 0.5°C but during the time step the actual temperature of the surface reached 0°C or above, then SNOWM would be routed down a no-melt path whereas in reality conditions for melt would be present. This can be overcome by broadening the temperature at which melt is said to occur, i.e. -0.5°C to +0.5°C (for example). This is not so physically correct (i.e. water freezes/ice melts at 0°C at one atmospheric pressure) but might result in a better representation of melt. The effect of increasing the temperature range over which melt/freezing occurs can be investigated once SNOWM is operational. It might result that there is no need to deviate from 0°C at all.

SNOWM then enters a section calculating the energy available for melt (17, 18, 19, 20 and 21).

(17) Net all-wave radiation, Rn, is calculated using the energy budget components calculated by TSTMsn.

$$Rn = S\downarrow - S\uparrow + L\downarrow - L\uparrow \qquad \text{Equation (1)}$$

Units : $Js^{-1}m^{-2}$

$S\downarrow$	solar insolation	short λ
$S\downarrow - S\uparrow$	surface absorption	"
$L\downarrow$	atmospheric IR emission	long λ
$L\uparrow$	greybody radiation	"

Surface absorption = % of the solar radiation absorbed by the surface, i.e. not reflected back into space. TSTM input file shows 1-albedo, i.e. 0.85 (= absorptivity) therefore = 0.15 i.e. 85% absorbed, 15% reflected.

e.g. Balick et al. (1981), fig. 2(b) 0800 hrs.

$$S\downarrow = 198, \quad S\uparrow = 198 \times 0.15 = 29.7$$
$$S\downarrow - S\uparrow = 198 - 29.7 = 168.3$$

(alternatively, $S\downarrow - S\uparrow = 0.85 \times S\uparrow = 168.3$)

$S\downarrow$ is calculated by TSTM allowing for the effects of aspect, cloudiness, cloud type, albedo, humidity, day and latitude, etc.

(18) The energy introduced into the snowpack by precipitation (enp) is a component of the total energy available for melt. If the precipitation is snow then enp is zero (19). If, however, it is rain, enp is calculated using equation (4), step (21). Equation (4) is taken from Male and Granger (1978), p.122. The importance of rain-on-melting snow appears to vary with climate and time of rain. In oceanic-type climates, e.g. British Columbia (west coat of North America) rain-on-snow is a significant energy input in the melt season. In contrast in the drier Prairies, especially the more northern areas) energy input due to rain-on-snow appears to be minimal. Timing of rain also appears to be important.

(20) The energy available for melt is calculated from an energy equation, equation (2). Energy available for melt $\mathcal{L}\rho_w M$ (or Q_m or enavm),

$$\mathcal{L}\rho_w M = R_n + c + e + g + p - \frac{dU}{dt} \qquad \text{Equation (2)}$$

R_n	net-all-wave radiation (equation 1), Q_n
$\mathcal{L}$	latent heat of fusion (Jkg^{-1})
ρ_w	density of water (kgm^{-3})
c	convection (sensible) heat exchange, Q_h. enc
e	latent (evaporation, sublimation, condensation) heat exchange, Q_e, ene.
g	heat exchange at ground surface, Q_g, eng
p	heat content of precipitation, Q_p, enp.
$\frac{dU}{dt}$	rate of change of internal energy of the snowpack

This equation is discussed, for example, in Male and Gray (1981, p.362), Kuusisto (1986) and Male and Granger (1978).

In SNOWM Equation (2) becomes:

$$l\rho_w M = \text{enavm}$$

i.e. $\text{enavm} = R_n + \text{enc} + \text{ene} + \text{eng} + \text{enp} \; (Jm^{-2}s^{-1})$

$\frac{dU}{dt}$ is taken as zero and is discussed by Male and Granger (1978, p.111).
The term B in Equation (3) is related to $\frac{dU}{dt}$ and therefore in the calculation of melt it is included. This is discussed in step (25).

The original format of Equation (2) was going to be:

$$l\rho_s M = R_n + [\text{constant} = 0]$$

However, it appears that ρ_w not ρ_s should be used and that to use a constant to describe the terms c, e, g and p would be invalid. It would be inaccurate to give g a value of zero when the ground temperature conditions and initial ground temperatuires are inputted into SNOWM for use by TSTM. Therefore, if g is not treated as zero, then the other factors c, e and p cannot also be treated as zero. These therefore have to be calculated, as does g. Step (21) calculates p and step (19) allows for p being zero if the precipitation is snow, not rain. Values for c, e and g corresponding to that time step should have already been calculated by TSTM (g has to be calculated because surface temperature does not equal ground heat flux). Therefore to obtain these values should be a relatively simple matter of extracting them from TSTM.

Originally the use of the constant instead of values for c, e, g and p was justified for climatic situations, such as Vermont (i.e. where air mass temperature does not fluctuate rapidly and frequently) because net radiation is the dominant factor affecting melt and not air temperature or rain-on-snow. However, as stated previously, g cannot be treated as zero if ground temperatures are input and included elsewhere in SNOWM (in TSTM) and if g cannot be treated as zero then neither can c, e and p. The use of c, e, g and p instead of a constant makes SNOWM much more flexible than it would have been with the constant, i.e. it should be able to encompass more varied meteorological situations, although, unfortunately, data requirements are larger.

(21) The energy supplied to the melting snowpack by rain is calculated using equation (4), from Male and Granger (1978).

(22) Is the energy available for melt positive (i.e. net incoming) or negative (i.e. net outgoing)? If enavm is negative then even though the pack is at 0^oC and therefore is ripe for melt, there is not sufficient energy available for melt (i.e. there is a net energy deficit). If enavm is positive then there is enough energy for melt and, as the pack is at 0^oC melt will occur. As scenario B is being discussed here, there is a net energy deficit and no melt occurs, SNOWM is routed to step (23).

(23) Is the precipitation snow or rain? If it is snow then no change in the snow volume/depth is recorded (as this has been done already (5)) and SNOWM is routed back to step (2) via (12). If the precipitation

is rain then the total amount of rain (multiplied by the area) is equal to the runoff for that time step. This therefore does not account for infiltration into the snowpack, i.e. all the rain falling in that time step is presumed to runoff in that time step. SNOWM is then routed back to step (2) via (12).

<u>C. Snow present - lack at 0° C, energy sufficient for melt to occur for the first time</u>

(1) to (21) as before (B).

(22) enavm is positive and therefore there is enough energy for melt to occur. SNOWM is then routed to step (25).

(25) Equation (3) is used to calculate melt rate and is derived from equation (2),

$$\mathcal{L}\rho_w M = enavm \qquad \text{Equation (2)}$$

$$M = \frac{enavm}{\mathcal{L}\rho_w B}$$

M	Snowmelt water equivalent rate (m water s^{-1})
enavm	Energy available for melt ($Jm^{-2}s^{-1}$)
ρ_w	Density of water (kgm^{-3})
$\mathcal{L}$	Latent heat of fusion (Jkg^{-1})
B	Thermal quality or fraction of ice in a unit mass of wet snow

B describes the amount of ice in a unit mass of wet snow. For example, if a pack was 25% water and 75% snow (ice), the energy available for melt should only apply to the 75% snow (ice) and not the pack as a whole, otherwise an overestimate of the melt rate will occur (the water would be 'accounted for' twice). Male and Gray (1981) suggest that a melting snowpack will generally retain 3 to 5% water (by weight) against free drainage, corresponding to a thermal quality (B value) of between 0.95 to 0.97. B is related to $\frac{dU}{dt}$ (see Male and Granger, 1978, p.111). k is now equal to one, as melt has occurred.

N.B: Melt is in water equivalent.

As an alternative to using the density of water (ρ_w) in equation 2, it has been suggested that the density of snow (ρ_s) be used. If the density of snow is used, then the melt rate will be in units of metres of snow/time unit rather than metres of water equivalent. This will make subsequent calculations of snow volumes considerably easier and in reality it is snow depth rather than water equivalents that are required. Hendrie and Price (1978) and Male and Gray (1981) both use the density of water in the calculation of melt rate, not the density of snow. This could be because they are viewing snowmelt from a specifically hydrological viewpoint, i.e. snowmelt is a phenomenon to be modelled and measured for inclusion in a much larger hydrological

model, therefore snowmelt water volumes are what are primarily required. It would seem logical to use the density of snow if snow volume is what is eventually required. If the density of snow is used then it has to be remembered that this changes with time, and this will have to be incorporated in SNOWM.

(26) Snowmelt is in water equivalent m/time unit. This can be converted to volume by multiplying by the area.

msnvol = M x area (in water equivalent or snow depending which density value is used)

snvol = snvol - msnvol

The new snvol feeds into the next time step run of SNOWM.

At present the generated meltwater is not routed anywhere. There are various routes that the meltwater could take, e.g. ponding on the snowpack surface, infiltration, etc. Where the water is located at the end of each time step is important. If the energy input drops in the succeeding time step, this meltwater may freeze. If this occurs, it will have to be melted again in a later time step.

The conversion of the melt rate into a melt volume by a simple multiplication of the cell area is alright until there is less than 100% snowcover (but this will only be registered when there is zero snow at the cell mid-point, in which case there is no melt anyway). Then, to multiply the melt rate by the total area of the cell would be incorrect, because, for example there would only be 75% of the area covered in snow). A way of solving this problem has yet to be found.

(27) Is p snow? If the precipitation is snow then no change is made to snvol and SNOWM is routed back to (2). If the precipitation is rain, then this is multiplied by the cell area and is added to the msnvol to achieve a total runoff volume for the cell during one time step.

(28) The heat convected into the pack by the rain, enp, has already been calculated, but the actual volume of rain falling on the pack, which convects this energy, still has to be added to any runoff total (if it is not accounted for by equation (4)). SNOWM is then routed back to (2).

D Snow present - pack at 0^{o} C, melting and melt in previous time step

As C expect steps 8, 29, 10 instead of 8, 9, 10.

(29) k = 1 therefore melting had occurred in the previous time step. When snow melts all the energy is used in melting the snowpack (latent heat of fusion) and the snowpack maintains 0^{o}C until melt is complete. When TSTMsn is calculating the surface temperatures of the snowpack the energy it is calculating, enavm, is used to heat/cool the snowpack. However, when the snowpack surface temperature reaches 0^{o}C because of the nature of water a phase change from solid to liquid

will occur. The snowpack will maintain $0^{o}C$ until all the snow has melted (fusion is complete), unless enavm decreases and fusion ceases because of lack of energy (in which case, snowpack temperature will probably decrease as well), see fig. 4a. When TSTMsn calculates surface temperatures (sntt) it does not allow for the energy needed to melt snow (latent heat effect) i.e. the maintenance of the snowpack at $0^{o}C$, but continues to use the energy calculated in heating the snowpack (fig. 4b). TSTM cannot therefore be used to calculate sntt as in stage (10). The surface temperature if melt occurred in the previous time step is therefore calculated by equation (5),

$$\text{sntt} = \frac{\Delta t.\text{enavm}}{\text{cp}\ \rho \text{s.d}}^{t-1} \qquad \text{Equation (5)}$$

Δt = change in time, i.e. one time-step (s)
cp = specific heat capacity of snow ($Jkg^{-1}K^{-1}$)
ρs = density of snow (here, in reverse of stage (25) it is possible the ρw and cp of water be used instead of those of snow) ($kgm.snow^{-3}$)
d = depth of snow (m)

Derivation:

$$\text{enavm} = \frac{T^{t} - T^{t-1}}{\Delta t}.\text{cp}\rho s \qquad (Jm^{-2}s^{-1})$$

T^{t} = temperature at time t (K)

$$\Delta t\ \text{enavm} = T^{t}-T^{t-1}.\text{cp}\rho s$$

$$\frac{\Delta t\ \text{enavm}}{\text{cp}\rho s} = T^{t} - T^{t-1}$$

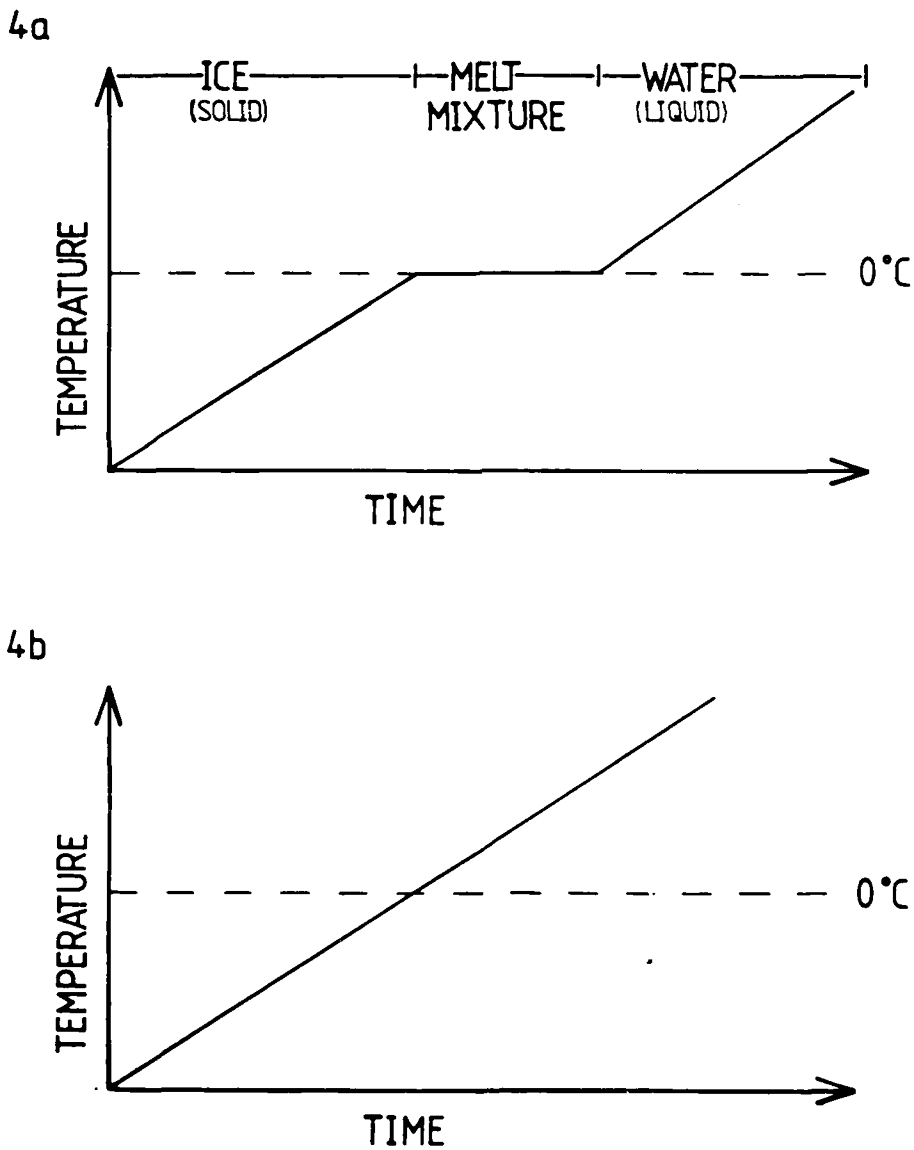
T^{t-1} = zero because melt occurred in last time step and therefore the snowpack should be equal to zero. therefore

$$\frac{\Delta t.\text{enavm}}{\text{cp}\ \rho \text{s.d}}^{t-1} = T^{t} \text{ (or sntt)}$$

The length of the time step t is important at this stage. If, for example, it was fairly long, eg. 6 hours, then within those 6 hours melt could have finished (faster melt in one time step than another) and in reality the newly exposed soil would be warming. Therefore the calculated sntt by TSTMsn would be wrong and T^{t-1} would not equal zero. If, however, a shorter time step is chosen, eg. 5 minutes, this problem is effectively alleviated (although SNOWM will take longer to run). It will be interesting to see if there is an optimum time step, i.e. one which minimizes both computing time and misrepresentation of energy use.

In equation (5) the enavm used is the current one, i.e. that which was calculated during the previous time step (step (20) has not been reached yet for that time step). This is valid because it is the surface temperature due to the results of the previous time step's melt that is being sought.

FIG.4: WATER TEMPERATURE AGAINST TIME DEMONSTRATING: (a) THE LATENT HEAT EFFECT. (b) EXCLUSION OF THE LATENT HEAT EFFECT.



E No snow present - melt finished, possible build-up of pack again by additional snowfall

Identical to A,B,C and D until (6)

(6) Snvol is greater than snvolcrit this time, even if there has been a small snowfall to add to the non-existent or minimal snowcover left after melting previously. SNOWM therefore switches into 'soil mode', i.e. 30, 31, 32, 33, 34, 35, 36, 37 and 38.

(30) TSTMsl is almost identical to TSTMsn except that soil characteristics are substituted for snow characteristics. k2 = k2+1 is a count to avoid allowing for precipitation being snow twice during the same time step. Each time TSTMsl is called k2 increases by 1. If SNOWM is solely in the 'soil-loop', i.e. stages 30, 34, 37/(35,36), 30, then it must have access to the data in stage (2).

(31) Is k2 = 1? i.e. SNOWM just switched from TSTMsn to TSTMsl. If 'yes' then precipitation being rain must be allowed for (32 and 33) and this is multiplied by area to get a runoff total (33). If the precipitation was snow then it is effectively ignored as allowance was made for snow in (5). If k2 is greater than one (i.e. TSTMsl was called in the previous time step) then the question of precipitation type is asked again (for the first time that time step).

(34) If the precipitation is rain then this is multiplied by area to achieve a runoff total (37) and SNOWM returns to (30), k2 = k2 +1. If the precipitation is snow then the snow volume is calculated, as previously (35). This is then compared with the critical snow volume (36). If it is found to be less than critical snow volume then SNOWM is routed back to TSTMsl (30). If, however, it is found to be greater than the critical value, SNOWM is routed to stage (3) via stage (38) which sets k and k2 to zero (i.e. no melt occurred in the previous iteration and (30) can be accessed for the first time again from (6)). k3 is set to 1 in (38) so that the precipitation and the snowpack volume $\geqslant$ snvolcrit stages (4,5,6 and 7) are avoided on first entering 'TSTMsn mode' from 'TSTMsl mode', by routing SNOWM to stage (8), stage (39). (38) has to be routed via (3) instead of directly to (8) because the energy budget components have to be recalculated using the snow characteristics instead of the soil characteristics. Therefore for the situation of the time step in which there is enough snow to change from TSTMsl to TSTMsn, TSTMsn will have to have the correct data for that time step. This will be investigated further.

All the units of SNOWM must be checked for consistency and any changes made. It must also be remembered that the snow albedo and other physical characteristics change with time; this must be modelled. It is proposed to do this by using some sort of time/depth count where, after a certain critical time/depth these characteristics will change.

Results

A meltrate 'contour' map can be produced using the meltrates derived

from stage (25). Simple linear interpolation between points will achieve this. The depth of snow is required for a ground temperature model. At present a pilot ground temperature model based on Nelson and Outcalt (1983) is in operation. It is as yet undecided how to represent areally the amount of melt and the associated spatial occurrence of snow. However, the percentage of the 'cell' area covered by snow can be calculated using Ferguson's (1984, p.54) equation:

$$A_{i+1} = (A_i^2 - V_i A_o / W_o)^{1/2}$$

A = area of snow at time i (km^2)
V = volume of melting during time i (water equivalent) ($10^3 m^3$)
A_o = initial snow covered area (km^2)
W_o = initial mean water equivalent volume of snow (mm)

Again, here, the units are water equivalents. It should be possible to change them to metres of snow.

D: Proposed schedule of work

(1) August - October

- Familiarization with TSTM
- Determination and abstraction of the variables required for the equations in sections B and C for inclusion in SNOWM
- Prototype catchment subdivision (map-based)

(2) Early October

Proposed visit to CRREL in order to:
- Meet Dr. Randy Scoggins (W.E.S., Vicksburg), and so to finalise computing details
- Evaluate in the field the prototype catchment subdivision with Dr. Tim Pangburn (CRREL)
- Viewing of test catchment W3, possible data acquisition and investigate experimental possibilities

(3) October to March
- Initiation and initial implementation of SNOWM
- Refinement and initial testing of SNOWM
- Possible experimental/field work over snowmelt season in collaboration with CRREL

(4) April onwards
- Development of experimental design for validation
- Further validation, refinement, testing, etc., of SNOWM
- Inclusion of vegetation in SNOWM

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